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CAPACITY OF NATURAL WATERS TO ASSIMILATE WASTES*

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CAPACITY OF NATURAL WATERS TO ASSIMILATE WASTES

Surface waters must continue to receive treated domestic sewage and residual wastes from industry. This is recognized as an essential and legitimate water use. One phase of this gargantuan problem is the determination of the capacity of surface waters to assimilate wastes. A corrollary is the correlation of industrial effluents with subsequent use of the receiving waters. The principles briefly discussed in this paper are: pollutional effects, elements influencing utilization, and self purification phenomena.

POLLUTIONAL EFFECTS

The term "pollutant" in its practical sense refers to any substance which alters the water receiving it in such a way that the value of the water for subsequent use is impaired. Normally the stream will contain a combination of substances with one or more offensive materials predominating. The effect of pollution may be very distinct whereas the cause is more often obscure.

Taste and Odor

These two properties are usually considered inseparable. In fact, most of the so-called tastes of water are believed to be registered through the olfactory nerves rather than the taste buds. Although they may have no hygienic significance, tastes and odors can make a drinking water extremely unpalatable.

Tastes and odors in water originate from both natural causes and man-made wastes. Cognizance must be taken of this fact because tastes and odors are rather imperfectly defined making it difficult to establish definitely the source of the objectionable substances. Certain species of algae are the most common natural offenders although leaves, grass, decaying vegetation,

and slime-forming organisms may contribute. Man-made wastes include industrial wastes and domestic sewage.

Phenols and phenolic equivalents are extremely objectionable in water to be treated for domestic use. Phenol reacts with chlorine to produce objectionable chlorophenol compounds. These compounds, even when highly diluted, may produce a taste and odor in water which could be described as medicinal, chemical, or iodoform.

Butadiene (from alcohol) and styrene manufacture produce highly odoriferous wastes which persist in streams. Mercaptan and other organic sulfur compounds represent trouble-makers for water plant operators. These are only a few of the compounds known to impart objectionable taste and odor to water.

Color and Turbidity

Color in a stream indicates the presence of waste materials which again may be of either natural or industrial origin. Runoff from boggy ground or forest areas is likely to be highly colored. Typical trade wastes having persistent color include kraft pulp, munitions, and leather tanning.

It is significant that color may persist in a waste even though it is biologically stable. In addition to aesthetic considerations, color presents a substantial problem in treatment of water for domestic use. There are several factors to be considered in determining the specific concentration of waste which will be unsightly in streams. These are: depth of water, light absorbing characteristics of the water and the stream bottom, turbidity, light source, hue, and angle of observation (1) (2).

Turbidity places added burden and cost on water purification. Indirectly, turbidity diminishes fish population through reduction in plankton and other forms of fish food. This comes about largely by retarding penetration of

light necessary for normal plankton development.

Oxygen Depletion

Dissolved oxygen in a stream is used in aerobic stabilization of organic wastes such as domestic sewage and the liquid discharge from food processing industries. Ferrous salts and sulfides are typical inorganic wastes exerting chemical oxygen demand.

It is not uncommon for deoxygenation of a polluted stream to proceed more rapidly than reaeration. If such conditions continue long enough, the dissolved oxygen in the stream will be depleted. Algae may cause temporary depletion of oxygen in the early morning hours and super saturation in the afternoon.

Sections of a stream void of oxygen constitute effective barriers to movement of fish. If the dissolved oxygen in a stream is reduced to a low level or is depleted for an extended period over a considerable length of stream, normal aquatic life will be either destroyed or driven to cleaner waters. Oxygen depleted waters may become unsightly, foul smelling, and offensive. They are not suitable for public water supply and are undesirable for recreational purposes.

Toxicity

Many substances may be toxic to biological life if the intake is great enough to produce a poisoning effect. There are minimum lethal values for some while others produce accumulative effects. Among those highly toxic to human, aquatic, and wild life are: arsenic, cyanide, chromium, sulfide, and radioactive wastes. The toxic effect varies with different fish species and in some cases may indirectly affect fish by destroying the food on which they feed.

Different waters vary greatly in their ability to assimilate toxic industrial wastes. A concentration of toxicant which may be harmless to fish

in one stream may be very harmful in another stream with water of different mineral content. Further, materials when combined may be much more toxic (synergism) or less toxic (antagonism) than they are in simple solutions. For example, a mixture of copper and zinc is several times as toxic as the individual components. Much remains to be learned regarding the toxicity of many substances and the chronic toxicity of most materials. Knowledge of the effect of exposure to low concentrations over long periods is essential to evaluation of toxicities.

Settleable Solids

Settleable solids deleteriously affect many uses of surface waters and, either directly or indirectly, practically all forms of aquatic life. Eroded soil is a major source of relatively inert solids which tend to blanket stream bottoms. Organic solids settle as stream velocities permit and in decomposing absorb some oxygen from the overlying water.

Costs of water treatment for both domestic and industrial uses are increased by the presence of solids. Finely divided materials such as sand, cinders, coke, and coal are very abrasive and will cause serious erosion of pumps and pipe lines. Dredging to maintain navigation channels may be substantially increased. Such materials as tar and oil coated solids are toxic to aquatic organisms. Under severe conditions the bottom biota are destroyed and the floor of the stream becomes an aquatic desert with no food to support the higher forms of life.

Oil

Damage to recreational facilities is one of the most serious effects of oil pollution. Floating oil or oil on beaches used for bathing are disagreeable to bathers and to others frequenting the shores. Oil coats the waterline

of pleasure craft thereby increasing their cost of maintenance. Oil polluted water at shore resorts definitely depreciates the value of such properties.

The damage of oil to commercial fishing is difficult to evaluate. In fact, some of the more hardy species may occasionally be observed in oil polluted waters. However, many forms of aquatic life, algae, protozoa, water fleas, eggs and larvae of fish are destroyed when coated with oil. This is believed to be the result of interference with normal respiration, transpiration, and photosynthesis. Except in cases of gross oil pollution, fish are probably most affected indirectly from reduction of their food supply by floating oil and oil coated settleable solids. The soluble constituents of crude oil are known to possess toxic characteristics, some crudes being greater offenders than others.

There have been numerous reports of destruction of waterfowl especially the migratory species like wild duck and geese. Heavy layers of oil, especially the lighter more volatile fractions, constitute a definite fire hazard as do oil soaked timbers. Oil slicks reduce reaeration in a stream.

Oil stains on the walls of sedimentation basins at water purification plants are unsightly and of aesthetic significance. Oil coatings on sand grains tend to compact the sand in water filters. Instances have been reported where oil was present in surface waters in sufficient quantities to reduce their value for livestock watering and for irrigation.

Acidity

The acidity of a water is usually caused by the presence of uncombined carbon dioxide, mineral acids, and salts of strong acids and weak bases. Acid neutralizes natural alkalinity in the stream. The most obvious damage from acid wastes are corrosion of metal structures and navigation equipment

and the disintegration of concrete sewers and masonry bridge piers.

Biota in surface waters are affected in a number of ways by acidity. It has a serious adverse effect on the plankton, particularly the microscopic green plants which contribute to the oxygen supply of the waters. Free mineral acids (pH below 4.0) apparently act directly and with lethal effect on the cells of minute plants and animals. Fish are affected in various and complex ways, an important one being damage to the respiratory system. The amount of oxygen which fish can utilize per hour, per unit of weight, varies greatly with the acid intensity. This can be correlated with the alkaline reserve of the blood which in turn is related to the carbon dioxide concentration. Acidity tends to prevent natural purification of surface waters by destroying or driving away animal and plant forms essential to this process.

Hardness, Salinity, Alkalinity

Calcium and magnesium ions in liquid wastes contribute hardness to receiving waters. Hard waters produce scale in hot water systems and increase soap consumption. Softening is universally practiced for boiler feed water but increased hardness adds to the cost of such treatment.

Brine from producing oil fields and various industrial processes is a major source of saline waste. High concentrations of dissolved solids in water tend to dehydrate and may destroy aquatic life, both plant and animal, through osmotic pressure effects. In addition, water treatment is made more costly and in extreme cases impracticable.

Alkalies causing pH values above 10.0 are undesirable and hazardous to fish in waters which are not naturally so alkaline. Fishes show disturbances of the cardiovascular and respiratory system if forced to live for even a few days in water which is more alkaline than pH 9.0. Alkaline waters dissolve

away the protective mucous from the gill filaments causing hemorrhages and stasis of the circulation. Changes in alkalinity affect physiological responses to certain substances. For example, the toxicity of ammonia increases greatly with increase in pH.

Nutrients

Certain elements such as nitrogen, phosphorus, potassium, and sulfur are essential for biological growth with the first two being basic nutrients. Liquid wastes containing these elements tend to stimulate plankton growth in surface waters. Plankton blooms are a nuisance and frequently create taste and odor problems in water treatment. Large masses of blue-green algae are particularly offensive. Fish, waterfowl, and livestock have been killed by toxic substances exuded from certain algae. Those interested in pursuing this subject will be interested in reviewing work done at Madison, Wisconsin (3) (4). Meat packing and milk processing plants are known to discharge wastes containing considerable quantities of nitrogen and phorphorus. Nitrogen removal alone does not solve the growth problem because phosphorus will support heavy growths of nitrogen fixing forms.

Radioactive Wastes

Pollution of a stream by radioactive wastes differs in several ways from pollution by domestic or industrial wastes. Radioactive wastes are not usually perceptible to the senses of sight, smell, or taste. They do not directly affect the oxygen resources of the stream, nor in the amounts usually discharged to a stream, do they exert a toxic effect toward aquatic organisms that industrial wastes of chemical origin sometimes do. On the contrary, some biological organisms, such as algae and other classes of plankton, may concentrate radioactive materials several thousand-fold over their water environ-

ment (5).

The radioactivity of the wastes cannot be neutralized by biological or chemical processes in a stream, comparable to the self-purification processes with which the stream renders domestic and most industrial wastes innocuous. Radioactivity is subject only to decay which is a function of time. The effect of radioactive wastes can be diminished greatly by quantitative and qualitative dilution in a stream. Qualitative dilution, commonly called isotopic dilution, is afforded by providing non-radioactive salts of the radioactive elements in the wastes. Inasmuch as an organism does not distinguish between the radioactive and stable forms of an element, it is less likely to take up a large amount of radioactive material than it would if only radioactive isotopes of the element were present. Quantitative dilution is dependent upon stream flow and mixing.

The value commonly used as a maximum permissible contamination of radioactivity in water used for drinking (6) purposes is 10^{-7} microcurie per ml. Streams consisting primarily of surface runoff have a natural background radioactivity much less than 10^{-7} microcurie per ml.

Because of the small amount of radioactive wastes discharged to streams, the public health problem is potential in nature and may be caused at present only by repeated exposure to, or ingestion of, aquatic plants or animals which have concentrated radioactivity.

The sources of radioactive materials occurring in a stream under normal circumstances are:

1. Natural background radioactivity
2. Nuclear reactor operations
3. Research activities in hospitals, universities, etc.

4. Industrial use

5. Fall out from experiments at Atomic Proving Grounds

Of these sources, only nuclear reactor operations and fall out from atomic bursts presently produce enough radioactivity to be of significance. Future expansion of research activities and industrial use may result in those sources becoming important factors in stream pollution but with reasonable care actual pollution can be avoided.

Temperature

In highly industrialized areas located along small streams, the stream water may be used over and over even by the same industry. This reuse frequently results in a substantial rise in temperature. Ordinarily, moderate temperature rise tends to stimulate biological activity. Temperature is an important consideration when the stream water is used for cooling purposes.

Pathogenic Organisms

Domestic sewage contains pathogenic organisms which die off gradually in the sewage and receiving water. Their survival time depends upon temperature, sunlight, water characteristics, and other factors. Some industrial liquid wastes also contain organisms pathogenic to man or animals.

Treatment methods to reduce the concentration of pathogenic organisms must be selected which are consistent with both subsequent use and dependable natural purification. Their concentration is greatly reduced by primary treatment processes and further reduced by secondary treatment. Chlorination may be employed to minimize the disease transmission role of sewage or other wastes.

ELEMENTS INFLUENCING UTILIZATION

There are numerous variables having bearing on use of a stream for waste disposal. Some of these have direct bearing on self-purification whereas others involve local and administrative considerations. Following is a general discussion of the more significant elements influencing stream utilization.

Physical Characteristics

The capacity of a stream to assimilate wastes is largely dependent on its physical characteristics. Such factors as discharge, slope, velocity, riffles, pools, depth of flow, channel roughness and configuration all play an important role. The type of bottom is a factor, whether rock, sand, or mud. Tides tend to slow down the velocity and may reverse the flow for short periods. Aquatic plants and shade from bordering vegetation influence photosynthesis.

All these factors have particular importance in the stabilization of organic matter by aerobic bacterial action and the restoration of dissolved oxygen by reabsorption from the atmosphere. The physical characteristics of a stream influence sedimentation, adsorption by attached bottom growths, surface areas available for reaeration, the rate of change of water at the air-water interface, and type and abundance of aquatic life.

Streeter from experiments on relatively shallow flowing streams of water drew the following conclusions (7):

"The rate of reaeration of the underlying body of water is governed primarily by the rate of adsorption of atmospheric oxygen at the water surface and secondarily by the volume of water and its temperature, depth, and relative degree of agitation.

"The rate of reaeration at the water surface appears to be practically independent of the volume of water underlying the surface, but is influenced by the temperature, oxygen saturation deficiency, and the degree of surface agitation of this underlying water. The latter is influenced, in turn, by the velocity of flow and, apparently to a slight extent, by the stream depth.

"The mean velocity of flow of the underlying stream has been shown to exert a powerful influence on the surface rate of reaeration, this influence being much less, however, below a critical velocity approximating 10 feet per minute, which appears to mark the point of transition from laminar to turbulent flow in the channels used for the experiments.

"Variations in the depth of flow have appeared to exert a slight influence on the surface rate of reaeration, possibly through their effect on the degree of surface agitation produced by a given mean velocity of flow."

Mixing in Streams

Dilution and short-circuiting of wastes in a stream are influenced by both lateral and longitudinal mixing. Lateral mixing refers to the rate at which pollutional material diffuses or spreads across the stream. Longitudinal mixing controls the speed at which a portion of waste moves downstream in advance of the theoretical detention period. Each type of mixing is a function of turbulence which in turn depends on physical characteristics of the stream, wind action, density currents, and temperature.

Full utilization of a stream to absorb wastes requires rapid dispersion. Rapid lateral mixing causes prompt diffusion of a waste with the entire flow thereby dissipating local concentrations that might be deleterious. In large slow moving streams, pollutional material may follow the shore for miles with relatively little lateral mixing. Each stream possesses individual character-

istics that govern mixing.

Longitudinal mixing influences the movement of pollution downstream and affects such self-purification factors as dilution, sedimentation, volatilization, and oxidation. It is related to short-circuiting of flow through deep rivers and lakes as a result of density currents. Mathematical parameters of longitudinal mixing have been derived and evaluated by Thomas and McKee (8). The basic concepts of longitudinal mixing have a significant influence on self-purification of streams.

Low Flow Frequencies

One of the most important factors in determining the capacity of a stream for waste disposal is the quantity of water available. The flow in a stream is a highly variable quantity, changing from day to day, and from hour to hour. Because the concentration of pollutants in the stream is inversely proportional to the quantity of flow, the low flows are of greatest interest. The probability of occurrence of low flows can be predicted from long time records of the stream's discharge. There are various methods for such low flow frequency analysis. Two methods are briefly outlined below; details of the procedures are contained in the references given.

One method for the presentation of minimum discharge data is the "duration curve," which is a plot of stream flow against the corresponding per cent of time that the discharge does not exceed each value (9). For example, if 10,000 days of record are available and on 16 of these days the flow was equal to or less than 20 cfs, a point would be placed on the plot at 20 cfs flow and 0.16 per cent of the time, and so on for all the curve. The preparation of duration tables and the plot is relatively simple but time consuming. Some time can be saved by tabulating and plotting the low flow portion of the curve

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only, say the lower 20 or 30 per cent. The portion of the curve at the extreme low-flow end may be expanded by use of probability paper. This makes the curve more serviceable.

A second approach to relating the occurrence of low flows with time is based on consideration of the extremes of drought flows in the period of record. Thus a record of 20 years would yield 20 minimum flow values, i.e., the minimum flow occurring for each year. These extremes are then analyzed. It has been observed that they often do not follow a normal symmetrical frequency distribution. Use has been made of a special skewed distribution curve developed by Gumbel for maximum flow (flood) predictions (10) (11). The flow data for low flow frequency purposes are arranged in order of increasing drought severity rather than increasing magnitude. Data which follow the distribution equation on which the skewed probability paper is based will plot as a straight line on this paper. This has the advantage of being able to project the straight line to less frequent flows for which data are not available.

Sometimes the plotted data show a distinct "break" or change of slope which renders the fitting of one straight line to the data appear unwarranted. In such instances the data are fitted with two straight lines, one for the portion of the data above the "break" and one for the data below.

Flow records ordinarily attainable are on a mean daily flow basis. Some engineers are of the opinion that longer periods for mean flow averages should be used for low flow frequency analysis, particularly where oxygen reduction is the problem. For instance a basis of weekly mean flows was used for one stream; this period corresponded with the time of flow to the point of maximum oxygen depletion. LeBosquet and Tsivoglou advocated use of an average two-week flow for one particular situation of a river stretch consisting of a pool behind a

dam. They called attention to a "lag period" which refers to an interval of time when discharge reaches a minimum and the dissolved oxygen reaches a minimum (12). The mean flow period for low-flow frequency analysis of a stream must be decided upon for each problem individually. On small streams with no pooling, mean daily flows may be the logical period to use.

In the case of mean flows below dams, the mean flow period selected is dependent principally on the duration of release of minimum flow. A minimum flow below the dam consistent with downstream water uses should be maintained. In such cases this flow should be considered that dependable and not mean daily flow or mean weekly flow of the unregulated stream.

In the use of records of flow it is necessary to establish that the data used in a duration plot are all obtained when natural conditions on the watershed are similar. The flows at many gaging stations are influenced by dams, diversion, or waste additions which have come about since records at the gaging stations began. Records used for a particular duration curve should be subject to the same factors so that they can be considered as belonging to the same statistical universe.

Self Purification Phenomena

Pollutional material in a stream may meet various fates. Organic matter under suitable conditions is utilized as food by bacteria and either oxidized or reduced to products such as carbon dioxide, water, methane, and others, leaving a relatively stable residue. Dissolved gases and volatile materials such as hydrogen cyanide and hydrogen sulfide may escape to the atmosphere. Certain materials may be oxidized chemically within a few minutes after contacting dissolved oxygen in the receiving water. Substances in the wastes

may react with substances in the receiving water, such as acids with alkalinity, changing their composition and altering their pollutional effect. Pathogenic bacteria and other organisms will discontinue reproduction in the receiving water and will die off because conditions of temperature, available food, etc., differ from their natural habitat.

A factor in utilizing a stream's capacity for waste disposal is the extent the materials in the wastes will be stabilized, dissimilated, destroyed, altered, or removed by self-purification by the time they reach downstream water intakes or points of additional pollution. In other words, the rate of stabilization or breakdown of the waste materials as well as initial concentration determines their concentration at a downstream point and the duration of their existence in objectionable concentrations. An important part of the stabilization of oxygen demanding materials is the extent to which the dissolved oxygen in the water will be decreased by such oxidation. A general discussion of this subject is contained in a subsequent section entitled "Stream Deoxygenation and Reaeration."

The rate of exertion of biochemical oxygen demand, which is synonymous to the rate of aerobic stabilization of the organic material, is influenced by the type of organic material present. This reflects the variation in the ease by which bacteria can oxidize different substances. Some work has been done on the determination of the rate of stabilization of specific industrial wastes and a few values are reported in the literature. Gotaas investigated the deoxygenation rate coefficients of sewage and concluded that the rate may vary considerably for different sewages (13). Williams found, on a fairly significant number of tests, that the rate coefficient of untreated sewage was significantly less than that of settled sewage (14). This was explained by

differences in availability of the particles settling out from that remaining, perhaps due to a size-of-particle effect.

The persistence of taste and odor producing substances is governed by self-purification factors. Ettinger and Ruchhoft in studies of the aerobic dissimilation of phenol and cresols in surface waters concluded that the rates of removal of these materials are governed by factors that control the metabolism of the microbiological agencies involved (15). These studies indicated that the rates of dissimilation of these compounds differed fundamentally from those of domestic sewage. They also concluded that the rate depended on the specific compound involved and that in any individual sample, the exact course which the removal of the phenolic compound would follow could not be accurately predicted.

Natural Pollution

The term "Natural Pollution" in its strictest sense applies to pollutional material which finds its way into surface waters from sources completely divorced from man. The line of demarcation between natural and man-made pollution is not distinct. In legal terms, natural pollution is recognized as inevitable drainage whereas man-made pollution is held to be preventable.

Principal sources of natural pollution include silt and dissolved salts from the soil together with organic materials extracted from vegetation and the soil. Soil erosion contributes tremendous quantities of inert materials annually to surface waters clogging navigation systems, filling reservoirs, and interfering with irrigation. Bennett has estimated that at least 3 billion tons of solid material are washed from fields and pastures of America every year (16). These solids blanket stream bottoms and drastically curtail both fish food and fish propagation. Microflora and fauna and higher plant and animal life in streams eventually die and contribute their share to pollution.

Professor Phelps has pointed out that natural pollution is the beginning of natural aquatic life (17). "The organic residues, picked up from the soil, provide the nutrient bases for the development of bacteria and of microscopic animal and plant life which in turn are food for successive life stages, worms, molluscs, insect larvae, and so on through forms of increasing complexity, up to the major fish life of the fresh and salt waters. Thus, these strictly pollutional materials play their own important role in the natural regimen of the stream."

Equitable Distribution

This objective has been well paraphrased by Chief Justice Holmes in his famous Supreme Court decision in the case of New Jersey vs. New York from which the following excerpt is taken, "A river is more than an amenity, it is a treasure. It offers a necessity of life that must be rationed among those who have power over it."

The natural purification capacity of surface waters is in reality a natural resource. In many cases, dilution alone is of paramount importance. It is only right and just that a fair share of this resource should be realized by each citizen and industry in a given drainage basin. The cost for protection and maintenance of this natural resource resolves into a problem of equity as based on scientific principles and factual information. Although true equity is utopia, it nevertheless is the goal.

The problems of equitable distribution range from simple dilution and apportioning of natural alkalinity to the more complex adjustment of oxygen demand where various rates of stabilization are involved. An equitable pollution abatement program thus becomes a cooperative venture with the stream control agency serving as referee.

In the case of industrial wastes, a base load must be established. This is not necessarily the existing waste load. There is reason to adopt as the base waste load, the residual wastes after industry has instituted in-plant improvements and has developed vigilant operation. This may include process changes and modifications, recovery measures, conversion to anhydrous processes, and all measures short of waste treatment. In fact, some industries may elect to curtail production during periods of critical stream conditions in lieu of providing waste treatment.

The degree of treatment must always be a function of stream use as related to the economic status of the area drained. This introduces apparent inequities within a given industry insofar as geographical considerations may be concerned. However, in most cases, there should be compensating factors and when the cost of treatment is made a production charge these inequities tend to neutralize.

Subsequent Water Use

In the final analysis, the extent to which a stream can be used for waste disposal depends on the economy of the area and the desires of its inhabitants. Domestic water supply is usually conceded to demand the highest water quality although some industrial process waters require even higher standards of chemical quality. The other extreme is the use of a stream for unregulated waste disposal. The subject of quality criteria for water use has been discussed in detail by McKee (18).

STREAM DEOXYGENATION AND REAERATION

The subject of dissolved oxygen depression and reaeration has been given such extensive treatment in the literature that a detailed presentation in this paper would be unsuitable. The phenomena is influenced by factors so numerous and so variable that exact formulation appears extremely difficult.

However, with sufficient information available the classical approach of Phelps and Streeter as refined or modified by Fair, Thomas, Howland, Tsivoglou and LeBosquet, and others, can in cases be used to arrive at rational and defensible decisions regarding utilization of a stream's oxygen assets.

The matter of "sufficient information" is what warrants the attention of industrial and municipal representatives. The gathering of the necessary information entirely by the regulatory agency for every stream is an enormous task. This is true because information most usable for establishing the capacity of a stream is obtained at times when conditions most nearly approach the critical. Critical conditions often appear at times of warm weather and low flow or perhaps during the operation of seasonal industry. Many years would be required for the field survey staff of most regulatory agencies to study all streams as thoroughly as is desirable. The task of gathering the necessary information might advantageously be undertaken by industries and municipalities with counseling and occasional aid from the regulatory agencies.

Instances are known where the industry has already obtained a great deal of useful information. All such information should be made available to the engineer analyzing the waste assimilating capacities of the stream in order that a sound decision may be arrived at to the mutual advantage of the industry and the regulatory agency. It is certain that an unsound decision failing to properly protect the stream will eventually be revealed. On the other hand one that is too conservative will be wasteful.

Concepts for formulating deoxygenation resulting from organic pollution and reaeration are discussed briefly in subsequent sections as an adjunct to pointing out what information is needed to apply them. There are cases where a great deal of field data has been obtained, yet that information had omis-

sions and inadequacies which prevented its being of maximum value for use with these rational methods.

Deoxygenation

The greater part of the organic matter of sewage and of many industrial wastes is capable of ready oxidation by bacteria. Such bacteria already accompany the waste or are rapidly developed by reason of the presence of the wastes in the stream. Progress in such oxidation is toward a stable residue having no further food value to bacteria.

Considerable time is required for biochemical oxidation to take place; time is, therefore, an important factor. Studies of the rate of biochemical reaction lead researchers to the conclusion that generally "the rate of biochemical oxidation of organic matter is proportional to the remaining concentration of unoxidized substance, measured in terms of oxidizability." (19). Basically this law which is similar to that of a monomolecular chemical reaction, indicates that the metabolic activities of the bacteria correspond directly with the available organic matter remaining at any time. According to Phelps, it appears that the rate of oxidation is so nearly monomolecular as to justify the use of such formula with the reservation that some facts suggest that the law does not always exactly express the situation.

The oxidation rate may be established for material in incubated bottles by measuring the use of oxygen after varying time periods extending over several days. From data relating oxygen use and time, the unimolecular rate coefficient can be computed. The least laborious method with a mathematical validity for this computation is the method of moments (20). Once the rate coefficient has been established the ultimate biochemical oxygen demand can be computed from data for the standard 5 day incubation period. This rate

should be established by an average of a number of determinations.

Formulation of biochemical oxygen demand necessitates dealing with ultimate demand because ultimate demands are the only values independent of time and rate. The term ultimate B.O.D. as used here refers to carbonaceous oxygen demand. Oxidation generally takes place in two stages, the carbonaceous material first and the nitrogenous material later. It has been demonstrated that these two stages may occur simultaneously and, therefore, it would appear necessary to consider nitrogenous demand in stream pollution. However, with some reservations, it is generally assumed that within the time elapsing up to the point of critical depletion, carbonaceous demand alone is significant. It is impractical to determine ultimate carbonaceous demand directly by incubation for extended periods because nitrogenous demand will appear. Uitlmate carbonaceous demands are, therefore, necessarily computed as previously described.

The rate of removal of oxygen demanding material from a stream may appear to be considerably different from the rate of oxygen utilization in incubated bottles. This can be explained as resulting from deposition of material and longitudinal mixing. Also in some streams biological growth on rocks, banks, and submerged vegetation are thought to act as adsorbents which serve to store the material so that the rate of oxygen utilization is increased.

Benthal Deposits

A certain amount of the oxygen demand of wastes or of natural pollution, is usually exerted by materials in suspension which, if appropriate conditions prevail in a receiving water, will settle out in bottom deposits. This material will undergo decomposition in the bottom deposits. Part of the stabiliza-

tion will be aerobic if the supernatant waters contain dissolved oxygen and part will be anaerobic, depending upon the thickness of the deposit. The oxygen demand satisfied anaerobically is in effect removed from the stream; therefore, such action would be an asset to the waste assimilative capacity of a stream from the oxygen depletion standpoint. However, there is always some interaction between sludge deposits and the supernatant water so that oxygen demanding material is being returned to the stream. If such return demand from accumulated bottom deposits is relatively high during critical conditions, sludge deposits may be a liability to maintaining desired oxygen levels. Jamsa and Akerlindh in an analysis of the curve of rate of sedimentation of sewage in a beaker concluded that a monomolecular formulation satisfactorily represented the data (21). Therefore, if a stream can be considered to represent a sedimentation tank, deposition of sludge would follow a monomolecular distribution from the source downstream.

Reaeration

Laboratory and field tests have indicated that the rate of solution of oxygen into unsaturated water is approximately proportional to the deficit of oxygen below saturation. The saturation value of oxygen in water is dependent mainly upon the atmospheric pressure, temperature, relative humidity, and chloride content.

The rate of reaeration in a stream is also influenced by water temperature, turbulence, the efficiency of the air-water interface film in transferring oxygen, and the depth of flow. Turbulence in turn depends upon stream velocity, depth, and roughness of the channel bed.

Temperature Effects

Temperature plays an important role in the dissolved oxygen levels of

streams. The rate of biological activity, and the rate of reaeration at the same deficit below saturation, increase with temperature. On the other hand, the saturation value of oxygen in water is considerably decreased with increase in temperature. Investigators have found various values for temperature correction coefficients to apply to monomolecular formulae of deoxygenation and reaeration. Monomolecular coefficients determined for one temperature can be converted to other temperatures. Also from data gathered at one temperature depletion of oxygen at other temperatures can be computed.

Recent research has indicated that the temperature correction factor for the reaeration rate coefficient is about the same as the generally accepted factor for the coefficient of deoxygenation. This conclusion is an important consideration in a simplified method of dissolved oxygen computations published in 1950 which is discussed later (12). It means that approximately the same oxygen deficits will prevail in specific situations, in which other factors remain constant, regardless of changes in water temperature.

The saturation value of oxygen in water decreases considerably with increasing temperature, thus rendering more serious reductions at higher temperature. Thus a reduction of 4 ppm at 20° C. leaves an oxygen content of 5.2 ppm while reduction of 4 ppm at 27° C. leaves only 4.1 ppm in the water.

Photosynthetic Action

Chlorophyll bearing plants in the presence of light convert carbon dioxide and water to organic compounds and release oxygen. Under certain circumstances this process takes place in submerged water plants such as algae and contributes oxygen to the stream. Light is necessary for this synthesis, consequently after sundown no oxygen is released and on cloudy days action is reduced. The plants also utilize oxygen in respiration but in relatively small proportion to that

produced. After sundown respiration continues through synthesis and oxygen release ceases. Under certain conditions, continued respiratory action may reduce the oxygen to such an extent as to cause distress to aquatic life. Consequently the presence of algae, particularly abundant algal growth, is not always an asset. Turbidity in the water interferes with growth of algae. Algae are not usually present in appreciable numbers in swift flowing streams.

From an engineering standpoint photosynthesis is not quantitatively predictable and hence not a reliable source of oxygen. It is important that photosynthetic action in a stream be recognized because dissolved oxygen results influenced by such action cannot be used in stream deoxygenation and reaeration computations. Hourly and daily variations of oxygen at sampling stations should be studied to determine critical conditions. An hourly fluctuation of oxygen in water containing heavy algal growth has been observed to be from 19.4 to 0.7 ppm as a result of photosynthesis and respiration.

Computations

Since 1925 with the publication of Public Health Bulletin 146 there have been available formulas for determining the effect of oxygen demanding pollution on the oxygen levels in a stream. Refinements and improvements have been developed since, one of the most recent of which is that of Thomas which may be made to take into account the effect of deposition and longitudinal mixing (22).

Of utmost importance to application of these formulations is the securing of adequate and suitable data, such as the concentration of oxygen depleting substances, dissolved oxygen levels, presence of sludge deposits, and existing photosynthetic activity in the stream under consideration.

The data should consist of replicate values of B.O.D., D.O. and flow at

each sampling station during conditions as near the critical as can be readily obtained. The stream capacity constants vary with temperature and turbulence of flow; such variations may introduce inaccuracies when estimates are made under flow conditions greatly different from those at the time of sampling. Extension of data to more critical conditions of lower flow and higher temperature gives equivocal results. Greater reliance can be placed in computations based on data obtained when conditions of flow and temperature are near the critical.

In applying the equations, it is necessary to divide the stream into a series of substantially uniform reaches. At points of marked changes in the channel cross-section or slope, or at points of significant additional pollution or dilution, new reaches should be introduced, each with its individual set of pollution load capacity constants. Precise estimates of the pollution load capacity of a stream may be formed only when the sampling stations are sufficient in number to divide the stream into reaches as individually homogeneous as practicable. The samples collected for B.O.D. determinations should be composited over a period of time long enough to average out variations in the character of the "slug" being sampled.

It is advantageous to collect samples at successive stations from the same mass of fluid as it passes down a stream. The variations of waste load should be studied and flow time determined so that the major pollutional "slug" is sampled at each successive station.

If it is not feasible to collect synchronized samples, the rate constants may be evaluated from mean values of a sufficient number of B.O.D. and D.O. determinations obtained during appropriate periods, provided that the amount

and composition of the organic pollution remains fairly uniform. In streams where disturbing influences, such as deposition and channel scour occur during the critical season, a considerable amount of data, including observations during periods of high flow may be required to establish the pollution load capacity with precision. Variations in dissolved oxygen throughout the day should be studied to evaluate photosynthetic activity.

Sets of data from samples collected at successive stations at times synchronized to sample the same mass of fluid constitute a homogeneous set for analysis. Values of the monomolecular coefficients of deoxygenation, reaeration and deposition should be computed for each homogeneous set of data. Determining the value of the deoxygenation coefficient requires measuring the demand exerted at different times - say one, two, three, etc. days - and the data fitted by the method of moment to the monomolecular equation (20). The deoxygenation constants obtained in this way, according to Thomas, will usually decrease going downstream from a point of pollution. This indicates that the remaining unoxidized organic matter becomes increasingly less available to the micro-organisms (22).

On small and medium sized streams, the flow and cross section usually increase as rapidly going downstream and points of significant pollution or dilution (tributaries) occur in such close succession that sampling points must usually be established at ends of short reaches. The dissolved oxygen concentration profile consists of segments of many oxygen sag curves, one for each of the successive short reaches. In some large streams, substantially uniform characteristics may prevail over long distances.

An important factor in the equation is the initial oxygen deficit below saturation. It has been found that even an unpolluted stream is seldom 100%

saturated with oxygen. Upstream waters which have received natural pollution to a considerable extent, present a special problem in the computations. In this case, extension of data secured at survey conditions to critical conditions of low flow and higher temperature involves a decision as to the upstream B.O.D. and dissolved oxygen content. For purposes of discussion, let us assume that the flow at survey conditions was about twice the expected drought flow which had been selected. One line of thought suggests that since the flow at critical conditions will be 50% less than that observed, the concentration of B.O.D. will be doubled, and oxygen deficits will be more severe. On the other hand, time of flow upstream will be considerably lengthened, consequently there will be more time for self purification which precludes a direct proportion relation. At drought flows it seems logical to assume that natural pollution will be at a minimum since inflow would be expected to be entirely subsurface drainage. The decision to be made is one of engineering judgment.

Flow-Deficit Relationship

Taivoglou and LeBosquet published a method which provides a simplified approach to the problem of estimating waste treatment requirements in order to maintain a given dissolved oxygen objective in a stream (12). The procedure has as a mathematic basis the Streeter-Phelps formula for oxygen deficit for the special case of the initial oxygen deficit equaling zero. In this case the formulations show that the maximum oxygen deficit is a function of only two variables, namely, the initial B.O.D. concentration and the ratio of the reaeration coefficient to the deoxygenation coefficient. This ratio is usually referred to in formulas by the term 'f'.

The formulations of the method may be developed as follows:

(a) $\frac{La}{Dc} = f^{\left(\frac{f}{f-1}\right)}$ Variation of equation 5c' by Fair (23)

Where: L_a = Initial B.O.D. concentration

D_c = Maximum Dissolved Oxygen Deficit

$$f = \frac{k_2}{k_1} = \frac{\text{Reaeration rate coefficient}}{\text{Deoxygenation rate coefficient}}$$

Assuming that 'f' is constant

(b) $$\frac{L_a}{D_c} = C_1 = \text{Constant}$$

If the term 'f' remains constant, then the maximum oxygen deficit is a function of the initial B.O.D. concentration only. Investigators have found that the deoxygenation and reaeration coefficients are affected by temperature in substantially the same manner, therefore 'f' may be considered independent of temperature. If the rate coefficients of deoxygenation and reaeration are not affected by factors other than temperature, 'f' may be considered a constant. The reaeration rate coefficient undoubtedly varies with different stages of flow, due principally to the effect of depth and turbulence on reaeration. However, for large and medium sized streams the variations of the rate coefficient other than with temperature may be expected to be relatively minor, if we consider only periods of relatively low flow.

For any one quantity of oxygen demanding material, the concentration of that material in the receiving water is inversely proportional to the quantity of dilution water.

(c) $$L_a \propto 1/Q \text{ or } L_a = \frac{C_2}{Q}$$

Where Q = Quantity of Flow in Stream

Substituting in equation (b)

(d) $$\frac{L_a}{D_c} = \frac{C_2}{D_c Q} = C$$

or $D_c Q = C_3$ Transposing for convenience $D_c = \frac{1}{Q} C_3$

The two variables D_c and $1/Q$ of the last equation, if plotted arithmetically, one as ordinate and the other as abscissa, will plot as a straight line. Though basically the same, this plot differs from that suggested in the original publication in that oxygen deficits are used rather than oxygen concentrations. The limits of the equation are theoretically zero and the saturation value of oxygen (which varies according to temperature).

Field observations of maximum oxygen deficits and corresponding flows will provide data for a plot of deficits against the reciprocal of the corresponding flows. A line of best fit will relate maximum oxygen deficits to flows. Temperature is taken into account when deficits read from the graph are subtracted from oxygen saturation values corresponding to the temperature being considered.

It is important to realize that this method applies in theory only to maximum oxygen deficit data, that is, the bottom of the oxygen sag curve. Maximum deficits do not necessarily occur at any sampling station. If the sag curve is rather flat near the low point, there may be a considerable length of stream in which the oxygen levels are for practical purposes the same. The point of maximum oxygen deficit will move upstream and downstream considerably as flow, temperature, and other factors vary.

As the flow becomes quite large ($1/Q$ approaches zero) the amount of dilution given the waste will increase. As a limiting condition, as the flow becomes infinite the dissolved oxygen deficit should approach zero. However, an unpolluted stream is seldom 100 per cent saturated with oxygen and a slight

deficit may be expected even at high flows.

Once sufficient data are obtained so that a line can be fitted to it, the line can be extended to cover drought flows during which data are not available. There are errors inherent in any such extension, therefore greater reliability is attained by obtaining data which minimizes the range of extension. The curve can be plotted from oxygen deficit, flow, and temperature data only, thus requiring a minimum of sampling, and laboratory work; that is, no B.O.D.'s need be determined. However, this may be false economy when decisions requiring large investments in treatment works are involved. If the initial B.O.D.'s are not known, the graph can be used to determine deficits corresponding to percentagewise changes in the initial load. If the initial B.O.D. load is known the plot can be used to determine the expected deficit from any load selected. Also the load corresponding to any selected deficit and flow can be computed. More confidence may be placed in plots of considerable data which can be analyzed statistically such as those discussed by LeBosquet and Tsivoglou (12).

An important consideration in such plots of critical deficits versus the reciprocal of the flows is that all data on any one plot must be the result of one uniform waste load (not concentration but total quantity). This limitation of the method can be avoided by plotting maximum deficits (D_c) against initial B.O.D. concentrations (L_a). This requires a determination of the B.O.D.'s whereas when D_c is plotted against Q and the waste load is uniform the B.O.D. need not necessarily be known. A simple calculation relates B.O.D. concentration, flows, and total quantity of B.O.D. All relationships of B.O.D. concentrations and corresponding maximum deficits can be used on a plot of L_a against D_c regardless of lack of uniformity of waste loads.

This method should be useful in many situations; however, its limitations

should be realized. Lack of agreement between the one basic assumption of the method that no initial dissolved oxygen deficit is present, with conditions generally prevailing has already been mentioned. However, if the initial deficit is of the order of, say, one part per million, little error would be involved in many situations. For example, as computed by the Streeter-Phelps formulation, for a stream with an 'f' value of 2, and an initial ultimate carbonaceous B.O.D. concentration of 20 ppm with no initial oxygen deficit, the maximum oxygen depletion would be 5.0 ppm. For the same situation and one part per million initial deficit the maximum deficit would be 5.6 ppm.

In the case of a number of sources of pollution along a stream at considerable distances apart, so that the stream is in various stages of depletion and recovery as it reaches the pollution sources, the relationship of deficit to flow would probably not be consistent.

The method of analysis does not yield information about the location of the point of maximum oxygen depletion. The method has no application for streams which empty into large bodies of water prior to the critical deficit being reached.

When sludge deposits create a major portion of the oxygen demand in the critical stretch, estimates of the required degree of waste treatment may be overly conservative when based on this method.

To eliminate or minimize the temperature effect, the data for this method are best observed within a relatively small temperature range, that is, under summer conditions at approximately 20° to 30° C. (12). As in other methods, dissolved oxygen data affected by photosynthetic activity of aquatic plants cannot be used.

CONCLUSION

Interest in determining the capacity of natural waters to assimilate wastes may be expected to increase in the future as greater emphasis is placed on water pollution abatement. It is hoped that the basic concepts discussed in this paper, together with reference to technical articles listed in the bibliography, will prove useful to those engaged in stream improvement work.

BIBLIOGRAPHY

1. Rudolfs, Willem, and Hanlon, William D., "Color in Industrial Wastes, Determination by Spectrophotometric Method." Sewage and Industrial Wastes, 23, 9, 1125 (1951).

2. Churchill, M. A., "Natural Reduction of Paper Mill Color in Streams." Sewage and Industrial Wastes, 23, 5, 661 (1951).

3. Lackey, J. B. and Sawyer, C. N., "Plankton Productivity of Certain Southeastern Wisconsin Lakes as Related to Fertilization, I. Surveys." Sewage Works Journal, 17, 3, 573 (1945).

4. Lackey, James B., "Plankton Productivity of Certain Southeastern Wisconsin Lakes as Related to Fertilization, II. Productivity." Sewage Works Journal, 17, 4, 795 (1945).

5. Kochtitzky, O. W., and Placak, O. R., "Radioactive Contamination as a Factor in Stream Sanitation Studies." Presented at Symposium on Radioactive Waste Problems and Treatment, 118th National Meeting, American Chemical Society, Chicago, Illinois, September 7, 1950.

6. U. S. Bureau of Standards, "Safe Handling of Radioisotopes." National Bureau of Standards Handbook No. 42, 1949.

7. Streeter, H. W., Wright, C. T. and Kehr, R. W., "Measures of Natural Oxidation in Polluted Streams. III. An Experimental Study of Atmospheric Reaeration Under Stream-Flow Conditions." Sewage Works Journal, 8, 2, 282 (1936).

8. Thomas, Harold A., Jr. and McKee, J. E., "Longitudinal Mixing in Aeration Tanks." Sewage Works Journal, 16, 1, 42 (1944).

9. "Water Quality Criteria," Chapter II. A report prepared for the state of California, Water Pollution Control Board by California Institute of Technology (June 1952).

10. Gumbel, E. J., "Floods Estimated by Probability Method," Engineering News Record, 134, pp 833-837, June 14, 1945.

11. Velz, C. J., "Graphical Approach to Statistics - Part III, Use of Skewed Probability Paper." Water and Sewage Works, 97, pp 393-400 (October 1950.

12. LaBosquet, M., and Tsivoglou, E. C., "Simplified Dissolved Oxygen Computations." Sewage and Industrial Wastes, 22, 8, 1054 (August 1950).

13. Gotaas, H. B., "Effect of Temperature on Biochemical Oxidation of Sewage." Sewage Works Journal, 20, 3, 441 (May 1948).

14. Williams, W. E., "Relation of B.O.D. to Stream Deoxygenation." Sewage and Industrial Wastes, 23, 9, 1161 (September 1951).

15. Ettinger, M. B., and Ruchhoft, C. C., "Removal of Phenol and Cresols from Natural Waters." Industrial and Engineering Chemistry, 41, 7, 1422 (July 1949).

16. Bennett, H. H., "Soil Conservation." McGraw-Hill Book Company, New York, N.Y. (1939).

17. Phelps, Earle B., "Stream Sanitation." John Wiley and Sons, Inc., New York, N.Y. (1944).

18. "Water Quality Criteria," Chapter V. A report prepared for the State of California, Water Pollution Control Board by California Institute of Technoloty (June 1952).

19. Streeter, H. W., and Phelps, E. B., Public Health Bulletin 146, U. S. Public Health Service, Washington (1925).

20. Moore, E. W., Thomas, H. A., Jr., and Snow, W. B., "Simplified Method for Analysis of B.O.D. Data." Sewage and Industrial Wastes, 22, 10, 1343, (October 1950).

21. Jansa, V. and Akerlindh, G., "A Method for Computing the Oxygen Curve in a Polluted Stream, with Special Reference to the Oxygen Consumption by Sludge Deposits." Sewage Works Journal, 13, 3, 551 (May 1941).

22. Thomas, H. A., Jr., "Pollution Load Capacity of Streams." Water and Sewage Works," 95, 11, 409 (November 1948).

23. Fair, G. M., "The Dissolved Oxygen Sag - An Analysis." Sewage Works Journal, 11, 3, 445 (May 1939).